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A Model-Based Approach to Risk Evaluation and the Assessment of Protection Provided by Water Intake and Treatment Systems

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ABSTRACT

This study presents an assessment of the protection provided by water intake and treatment systems against potential health risk to water consumers. To perform the assessment a case study was conducted involving modelling and risk assessment based on scenarios of decreasing water quality at the intakes (i.e. emergency situations). The study sites were two continuously operating water treatment plants in Southern Poland (CEE). The study material were the results of tests conducted in the years 2012–2019 on samples of water taken directly at the intakes and samples of treated water. The samples were used to determine the concentration of selected metals (Cd, Cr, Mn, Ni, Pb and Zn), organic pollutants (benzo(a)pyrene, benzene, acrylamide, epichlorohydrin, vinyl chloride and 1,2-dichloroethane) and bacteriological pollutants (*Coliform* bacteria, *Escherichia coli*, *Enterococcus faecali* and *Clostridium perfringens*). The non-carcinogenic (HI) and carcinogenic (CR) hazard indexes were estimated based on the quality of water at the intake using linear regression models. The risk values obtained were compared with permissible values specified in the US EPA methodology. It was demonstrated that the concentrations of the xenobiotics analysed in treated water would have to increase 11 times in the case of adults and 29 times in the case of children before the risk level related to drinking water exceeded permissible values. In the least favourable exposure scenario modelled, assuming the presence of organic xenobiotics in potable water, the total HI amounts to only 10% of the permissible value in adults and 1.5% in children. The total CR calculated for the 3-times lower water quality did not exceed permissible values, which proves that the water treatment systems are safe.

Keywords: variability of health risk, metals, organic compounds, microbiological pathogens, safety of public water distribution systems.

INTRODUCTION

Water treatment plants (WTP) and water distribution systems are considered critical infrastructure [National Program, 2018]. Therefore, it is imperative from the standpoint of social responsibility that they are capable of an immediate reaction to emergency situations. Having an in-depth knowledge about sudden (incidental) degradation of water quality and the possible health hazard for water consumers is important for providing population security. The new Directive (EU) 2020/2184 of the European Parliament and of the Council on the quality of water intended for human consumption [DW EU 2020/2184] requires an even more restrictive approach to the protection of health of consumers of water supplied using public water distribution systems. This document creates new challenges for public water distribution system operators, including the introduction of risk management applicable to their entire operation – from the intake of water to the delivery of water to end consumers.

Health risk assessment is not a new research tool. However, the application of this methodology to the assessment of safety of operational water intake and distribution systems is still rare. The estimation of health risk posed to consumers using water with specific physical, chemical and microbiological parameters is an answer to the possible negative impact on their health caused by hazardous factors e.g. the occurrence of waterborne illnesses [Wichrowska et al., 2001]. The problem of assessing health risk related to the physical and chemical parameters of water, such as the presence of potentially toxic elements or xenobiotics, has been analysed by e.g.: Wongsasuluk et al. [2013], Junhua et al. [2018], Yang et al. [2012], and Izquierdo et al. [2015]. These authors conducted research related to the presence of metals and semi-metals in water. On the other hand, Zhang et al. [2019], Song et al. [2019], Karyab et al. [2016], McMahon et al. [2017] and Walaszek et al. [2020] determined the concentration of xenobiotics in potable water. The review of the subject literature showed that there is an insufficient number of papers on the evaluation of health risk related to water delivered to consumers. The scientific literature does not contain any comprehensive studies on the modelling of health risk and this subject is not sufficiently popular. After reviewing international publications, the authors noticed how much remains to be done with regard to health risk related to the presence and effects of hazardous, often carcinogenic, substances in potable water and how serious this problem is for the entire human population.

The present study is an assessment of the protection provided by water intake and treatment systems against potential health risk to water consumers. The main purpose of the analyses was answering the following question: To what extent does the quality of water at the intake have to deteriorate before the health risk posed by water supplied through the distribution system becomes unacceptable?

The detailed goals of this study were to:

1) Identify emergency situations generating potentially increased health risk based on the analysis of data collected in the years 2012–2019;
2) Assess the variability of health risk posed by water from the public distribution system depending on potential negative conditions applicable to water at the intakes;
3) Assess the protective function of water treatment technologies in providing consumer health safety.

Characteristics of the study area

The study area for which the assessment of health risk posed by water from the public distribution system was performed includes surface and underground water intakes located in Southern Poland (EU), specifically in part of the Carpathian Orogen – the Beskid Sądecki Mountain Range. The water intakes supply two large water treatment plants: in Stary Sącz (WTPss) and in Świniarsko (WTPs).

WTPss is supplied with water from:

- a bottom infiltration intake in the Dunajec River,
- a group of 16 infiltration wells (supplied naturally and artificially using a system of 3 groups of basins providing surface water from the same river).

WTPs is supplied with water from:

- a surface intake in the Dunajec River,
- a group of 16 infiltration wells located in Świniarsko (supplied with surface water from the same river through an uncovered watering ditch),
- a group of 11 infiltration wells located in Mała Wieś [Wysowska et al., 2021].

Well intakes

Multiple-bore wells supplying WTPss and WTPs are located within the High Yield Aquifer no. 437 – Dunajec River Valley (Nowy Sącz) and also in the Group of Groundwater Bodies no. 166 (designation JCWPd PLGW2000166). The high yield aquifer is porous and contains 1.6 thousand m^3/h (i.e. 39.5 thousand m^3/d) of water. The filtration rate of the quaternary water-bearing formations is 8.5–850 m/d. The wells used by both water treatment plants are characterised by relatively high natural resistance to pollution. This applies especially to wells located further away from the river valley. The intakes in Świniarsko, Mała Wieś and the wells in Stary Sącz are located in a cut-and-fill and non-flood terraces and have medium susceptibility to pollution originating from the land surface [Wysowska et al., 2019]. Wells located near the river are characterised by high and very high susceptibility to pollution. This is the direct result of hydrogeological parameters and the geological structure of the region [Wysowska et al., 2019]. However, it is the vertical transport of pollutants and the type of formations (sediments) in the vadose zone that have the biggest impact on the susceptibility of the aquifer to pollution.

Intakes in the Dunajec River

The Dunajec River is the main surface watercourse in Southern Poland and a right tributary of the Vistula River. Its river basin has a surface of 6804.1 km^2 and its total length is 248.2 km [Paczyński & Sadurski, 2007]. The average ground water run-off of the Dunajec River is 9–12

$dm^3/(s·km^2)$ and the average flow at a measurement station located in Stary Sącz is 67.8 m^3/s [Kicińska, 2016; Kicińska & Wysowska, 2021].

Geomorphological and hydrogeological conditions at the intakes result in a high share of groundwater flow and surface flow in the overall flow towards the Dunajec River valley. The average annual rainfall in the area analysed is about 700–800 mm (>500 mm in summer and 250–300 mm in winter). The occurrence of cloudbursts in summer results in the risk of flooding, which is an adverse phenomenon in foothill and mountain areas. As a result, the two surface intakes in the Dunajec River (in Stary Sącz and Świniarsko) are at risk of emergency situations in the form of fluvial flooding and pluvial flooding. Dunajec is a typical mountain river with freshets occurring in spring (caused by thaw) and in the summer-autumn period (caused by cloudbursts). These can result in damage to surface water intakes, as was the case in Świniarsko in 2014 during heavy flooding (Fig. 1). The risk of such emergencies requires providing technical protection for the water intake structures as well as technological protection for the water treatment processes. River floods cause considerable degradation of water quality at the intakes and carry water with higher turbidity, reaching from several to several hundred NTU (Nephelometric Turbidity Unit) (Fig. 2).

Since both of the facilities studied (WTPss and WTPs) are supplied mostly with water from surface intakes in the Dunajec River (as of March 2022 the share of river water amounts to 46%) and the groundwater supplied from wells has infiltration properties, the authors selected floods as natural emergencies that potentially increase human health risk.

This study does not take into account potential emergencies in the form of technical failures. Having analysed the multiple-year history of the

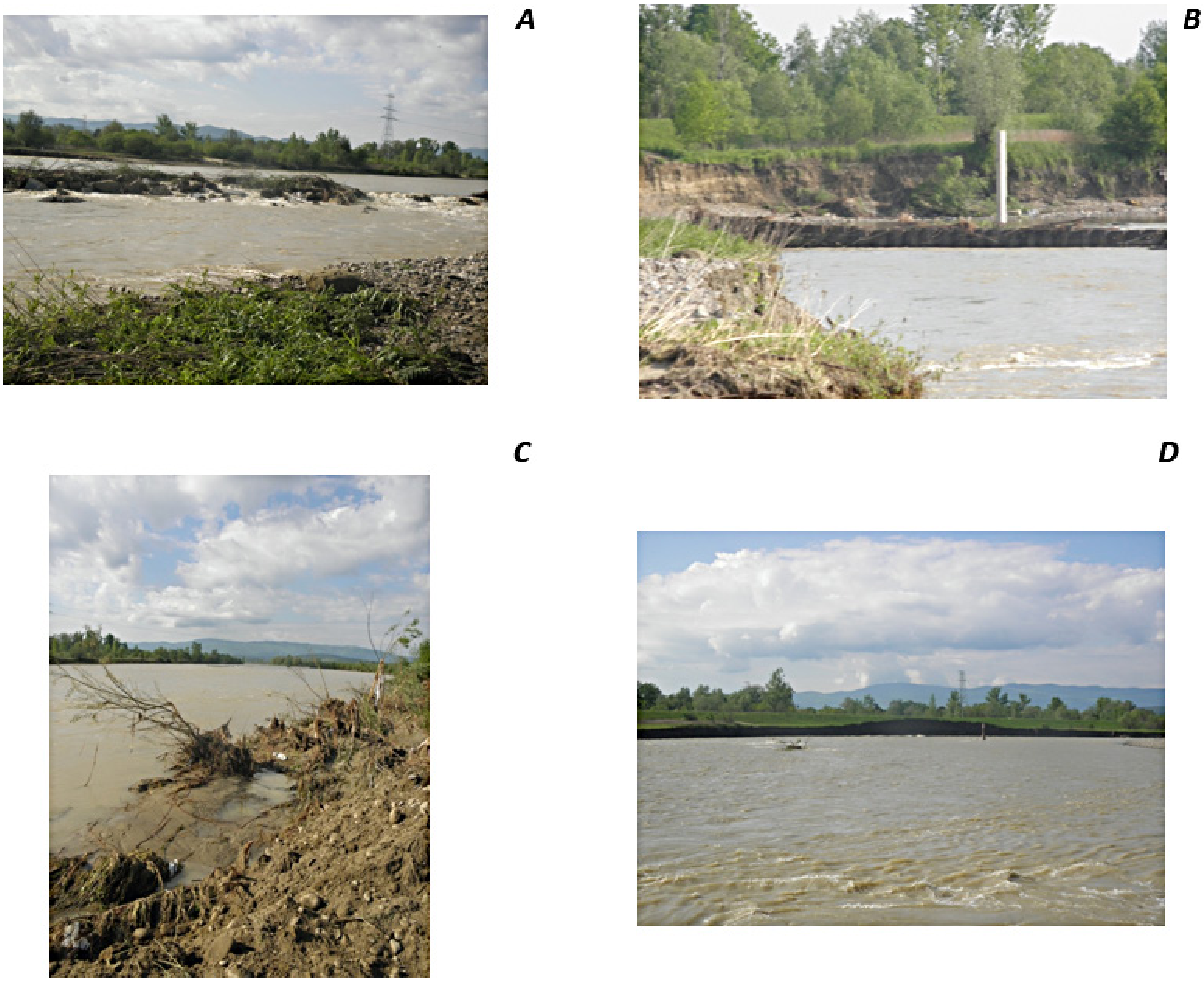


Figure 1. Photographic documentation of the damage to the area of the surface intake on the Dunajec River in Świniarsko in 2014: branches and rubble deposited by the floood wave (A); damage to the river banks (B-C); damage to the flood embankment on the other side of the intake (D) [WTP archive]

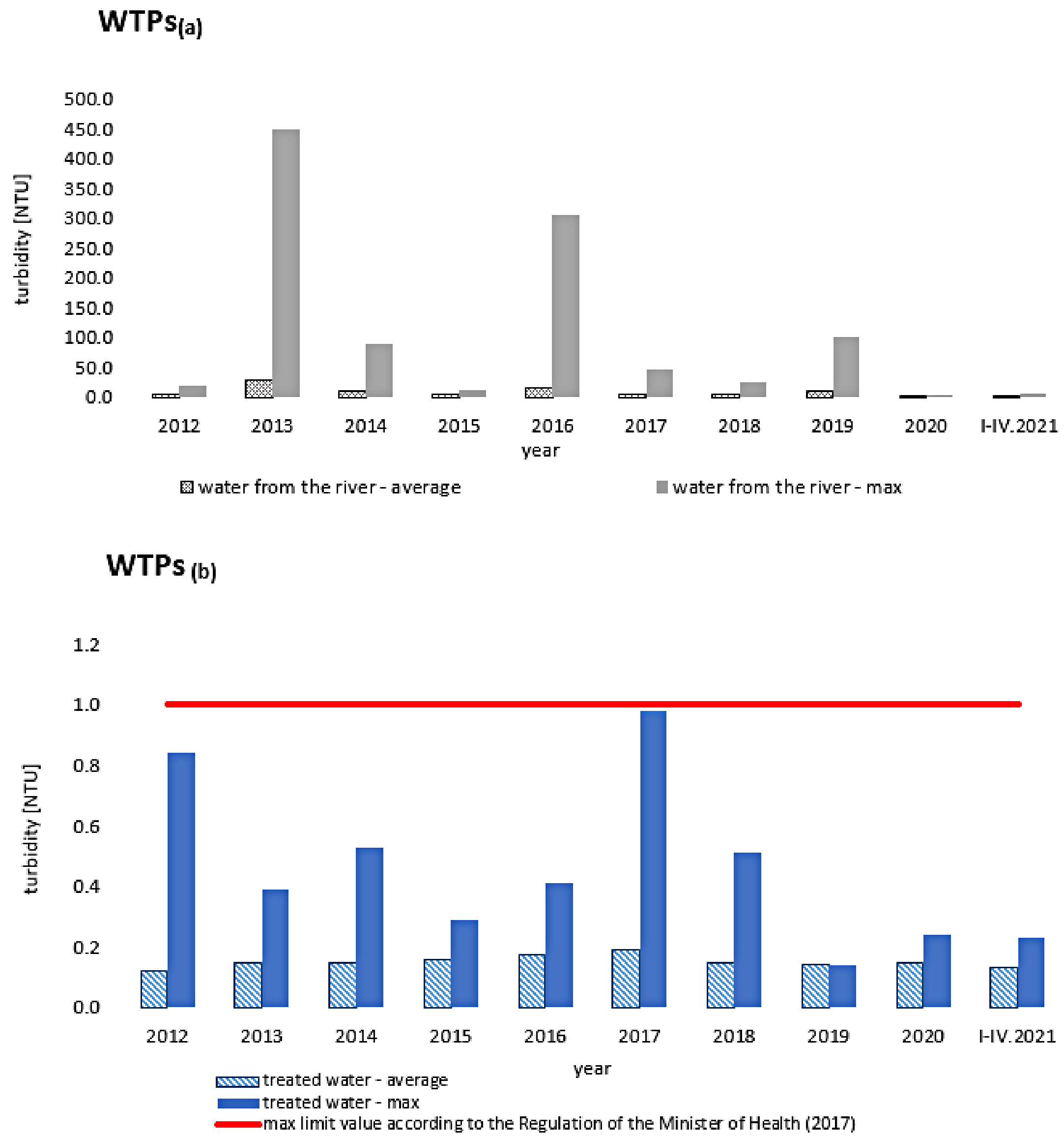


Figure 2. Turbidity variability in water from the Dunajec River (a) and treated water (b) WTPs in 2012-2021 [Wiewiórska et al. 2021a; Wiewiórska et al. 2012b]

technological processes at the water treatment plants studied, the authors found that there were no failures of this type that affected the quality and safety of water supplied to the public water distribution system. Additionally, both water treatment plants have process-related procedures in place for the event of failure of individual sections of their process lines and control systems as well as an approved Water Safety Plan [Water Safety Plan, 2019]. The latter document plays a very important role in the preventative preparation of the public water distribution systems for various emergencies. It lists the procedures that should be followed in various emergencies and crisis situations to maintain water supply safety [Zimoch & Mulik, 2019].

Water treatment plants in Świnarsko and Stary Sącz

The water treatment plants selected for the study supply potable water to over 100 thousand consumers (as of 31.03.2022) and are considered a critical part of the public water distribution system. The maximum capacity of WTPss is 14 000 m^3/d and the maximum capacity of WTPs is 16 800 m^3/d. The plants use a 3-stage and a 4-stage technological process, respectively, which is the most comprehensive water treatment system, and are suitable for treating A2/A3 category water. In accordance with the Regulation of the Minister of Maritime Economy and Inland Navigation [Regulation, 2019] water belonging to these categories requires:

- simple physical treatment, especially filtration and disinfection (category A1);
- standard physical and chemical treatment, especially pre-oxidation, coagulation, flocculation, decantation, filtration and disinfection through final chlorination (category A2);
- highly efficient physical and chemical treatment or biological treatment, especially oxidation, coagulation, flocculation, decantation, filtration, adsorption in activated carbon, disinfection through ozonisation or final chlorination (category A3).

However, the actual data from monitoring of physical and chemical properties of water in the Dunajec River [collected from the archives of Sądeckie Wodociągi Sp. z o.o.] indicate that the concentrations of substances in water are mostly within the limits set for surface water categories A1 or A2 [Regulation, 2019]. The results of chemical analyses performed for monitoring purposes indicate that the composition of water taken from the river in the preceding ten years (i.e. 2012–2021) is stable.

The detailed description of technological processes can be found in a previous publications by the authors [Wysowska et al., 2021]. Therefore, the present study will only focus on the assessment of the resistance of water treatment technologies to emergencies in the form of considerable degradation of water quality at the intakes. The description of water treatment plants includes the information that they received additional equipment and are prepared to treat surface water that is characterised by most demanding, varying parameters. WTPss is suitable for the treatment of surface water that belongs to category A2 and/or A3. The plant uses: coagulation combined with sedimentation in vertical sedimentation tanks, filtration in a high-rate anthracite-quartz filter with contact coagulation, ozonation, filtration in activated carbon bed filters and final disinfection using UV light and chlorine gas. WTPs uses: coagulation, sedimentation, contact coagulation in Dyna-Sand sand filters with added coagulant, disinfection using UV light and disinfection using chlorine gas. The treatment technologies allow for effective removal of physical and chemical pollutants, including organic and inorganic compounds, from water. It is also possible to remove heavy metals and biological contaminats, including *Coliform* bacteria, *E. coli*, *Enterococcus faecali* and *Clostridium perfringens*. The effectiveness of these methods has been studied and confirmed in a study by Wysowska et al. [2021].

The technological processes at both water treatment plants are specifically designed to work in conditions of highly variable river water turbidity, as this characteristic has a considerable impact on the treatment processes (Figure 2). At WTPss, depending on the quality of surface water at the intake, river water can be treated in one of the two processes: (1) water is supplied directly to WTPss or (2) water is supplied artificially to the aquifer through systems of infiltration basins. Depending on its physical and chemical properties, water artificially feeds the aquifer is subject to one of the three treatment processes:

- variant I (NTU ≥20 and in cloudburst and flooding conditions) – water is subject to phase I of treatment and pretreatment in a Lamella separator and sent to infiltration basins;
- variant II (NTU 5–10) – water is subject to pretreatment in a Lamella separator and sent to infiltration basins;
- variant III (NTU 2–5) – surface water is sent directly to the aquifer [Kicińska & Wysowska, 2021].

MATERIALS AND METHODS

The study material were the results of analyses conducted on raw and treated water samples collected in the years 2012–2019 to determine the content of:

1) Potentially toxic elements (metals): Cd, Cr, Mn, Ni, Pb and Zn (*n=180* samples collected in the years 2012–2017 at WTPss) [Kicińska & Wysowska, 2021].
2) Organic xenobiotics: benzo(a)pyrene, benzene, acrylamide, epichlorohydrin, vinyl chloride and 1,2-dichloroethane (n=18 samples collected in the years 2012–2019 at WTPss and WTPs). As the test results pertained to treated water supplied to the water distribution system by both water treatment plants and they were close to the limit of quantitation for a given parameter, the worst possible scenario was used in the risk assessment, i.e. the concentration of xenobiotics lower by an order of magnitude than the method's limit of quantitation (LOQ) [Wysowska & Kicińska, 2021].
3) Bacteriological pathogens: *Coliform* bacteria, *Escherichia coli*, *Enterococcus faecali* and *Clostridium perfringens* (n = 8973 samples collected in the years 2015–2019 at WTPss and WTPs) [Wysowska et al., 2021].

The statistical analyses and the characteristics of the material collected are presented in the publications mentioned above, therefore the authors decided not to include them in the present paper.

The parameters listed above were selected for risk assessment due to their prevalence in the environment and their toxicity. Metals (Cd, Cr, Mn, Ni, Pb and Zn) and organic xenobiotics are anthropogenic pollutants, produced mostly by various industries or originating from emissions at low altitudes (VOC) [Kabata-Pendias & Szeke, 2012; Kicińska, 2018]. The results of microbiological analyses were included due to the observed prevalence of human exposure to bacteriological pollution resulting from the use of untreated water [Wysowska et. al., 2020].

Water samples were collected in accordance with standard PN-EN ISO/IEC 17025:2018-02. The content determination for the parameters analysed was performed in the following way:

- dissolved metals: using the ICP-MS Elan 6100 device by PerkinElmer (LOQ for the elements analysed of $2 \cdot 10^{-3}$ mg/dm^3);
- organic xenobiotics: at an accredited laboratory in Pszczyna (accreditation no. AB 1232) based on the following standards: benzo(a) pyrene: KJ-I-5.4-97 based on standard PN-EN ISO 17993:2005 and following research procedure KJ-/I-5.4-13C; benzene: based on method KJ-I-5.4-155 in accordance with standards PN-EN ISO 15680:2008 and PN-EN ISO 11423-1:2002; epichlorohydrin: in accordance with standard PN-EN 14207:2005; acrylamide: based on methods KJ-I.5.4-94 and EPA Method 8032A 1996 and in accordance with KJ-I.5.4-14C; 1,2-dichloroethane: based on method KJ-I-5.4-155 in accordance with standards PN-EN ISO 15680:2008 and PN-EN ISO 10301:2002; vinyl chloride: based on method KJ-I-5.4-155 in accordance with standards PN-EN ISO 15680:2008 and PN-EN ISO 10301:2002;
- microbiological pathogens: at an accredited laboratory specialising in water and sewage analyses (accreditation no. AB 980) using plate method and membrane filtration method, based on standard PN-EN ISO 7899–2:2004 for *Enterococcus faecalis* and standard PN-EN ISO 9308–1:2014-12 + A1:2017-04 for *Coliform* bacteria and *Escherichia coli*, and in accordance with Directive 98/83/EC for *Clostridium perfringens*.

The risk assessment used the maximum recorded values of individual parameters, which reflect the poorest water quality conditions to date. The health risk assessment was based on regression models based on the following relationship: assigned substance concentration → dose taken in → exposure level. The assessment was performed in the following way:

1) in the case of xenobiotics, the maximum determined values of individual parameters were multiplied to reach an increase by 5%, 25%, 50%, 100% and 200% of the actual recorded maximum annual value of a given parameter (CW).The analysis used the following linear regression models to estimate non-carcinogenic and carcinogenic hazard indexes (HI and CR, respectively) expected in the case of a dramatic decrease in water quality:
   - M_0 - regression$_0$ model – based on the actual total maximum concentration of xenobiotics (CW_0)
   - M_1 - regression model$_1$ – based on the assumption that: $CW_1 = CW_0 + 0.05 \times CW_0$ (1)
   - M_2 - regression model$_2$ – based on the assumption that: $CW_2 = CW_0 + 0.25 \times CW_0$ (2)
   - M_3 - regression model$_3$ – based on the assumption that: $CW_3 = CW_0 + 0.5 \times CW_0$ (3)
   - M_4 - regression model$_4$ – based on the assumption that: $CW_4 = CW_0 + CW_0$ (4)
   - M_5 - regression model$_5$ – based on the assumption that: $CW_5 = CW_0 + 2 \times CW_0$ (5)

The non-carcinogenic hazard quotients ($HQ_{1,2,..n}$) for a given substance and for a given exposure route (ingestion, inhalation) were used to calculate the total hazard index ($HI_{oral/inhal}$) using formula no. 6 [US EPA, 1989]. The obtained results were then compared with the variability of both non-carcinogenic (HI) and carcinogenic (CR) exposures according to the principle of risk additivity (formulas No. 7 and 8):

$$HI_{oral/inhal} = HQ_1 + HQ_2 + ... HQ_n \quad (6)$$

where: $HI_{oral/inhal}$ – total hazard index for exposure through ingestion or inhalation [-]; $HQ_{1,2,..n}$ – hazard quotient for each chemical substance for a given exposure route [-].

$$\text{Total HI} = \sum_{i=1}^{n} HI_1 \quad (7)$$

$$\text{Total CR} = \sum_{i=1}^{n} CR_1 \quad (8)$$

where: HI_1 / CR_1 – non-carcinogenic / carcinogenic hazard index for a given exposure route;
n – quantity of substances taken into consideration during risk assessment.

The risk values obtained through the modelling were compared with permissible values specified in the US EPA [1989] methodology by calculating parameter values generating unacceptable exposure levels.

2) In the case of the metals analysed, two years with the highest variability of parameters (2012 and 2017) were used in the assessment. In those years, the highest concentrations and the highest standard deviation were recorded for Cd, Cr, Ni and Pb, while Mn and Zn in the samples from the Dunajec River were characterised by the highest dispersion [Kicińska & Wysowska, 2021]. As discussed in the study by Kicińska & Wysowska [2021], ingestion is the main exposure route for metals in water. However, the risk assessment takes into consideration two exposure routes: oral (ingestion) and dermal, both for children and for adults. Assuming a strong linear correlation between the exposure level and concentration of a given metal, an unacceptable HI value was calculated and used to establish the corresponding parametr concentrations.
3) An assessment of bacteriological pollution was conducted based on the assumption that the presence of just 1 bacteria (CFU/100ml) amounts to an unacceptable risk level [Regulation, 2017].

The proposed approach may become a tool supporting the management of health risk and operational safety of public water distribution systems.

RESULTS AND DISCUSSION

Assessment of risk related to the presence of metals in water

The total hazard index (HI) for the dermal and ingestion routes in children and adults stemming from the concentrations of the metals analysed in water supplied to the distribution system was 8.26E-02 and 1.21E-02 in children (in the years 2012 and 2017, respectively) and 1.71E-01 and 2.53E-02 in adults (in the years 2012 and 2017, respectively). The actual calculated HI related to the use of water by children and adults ranged between 1.2–2.5% (children and adults in 2017) and 8.3–17.1% (children and adults in 2012) of the permissible level (which equals 1). The calculations demonstrated that the total hazard index (HI) would have to increase by between 82.86% (in 2012) and 97.47% (in 2017) in the case of adults and by between 91.74% (in 2012) and 98.79% (in 2017) in the case of children to exceed permissible levels.

The ingestion route comprised between 84.46% and 92.40% of the calculated risk level in the years analysed (2012 and 2017). As the ingestion route had the largest impact on the risk level, this scenario was used in further exposure modelling. Results from 2012 were used in the assessment due to the highest actual share of ingestion exposure determined for that year. Assuming empirical multiplication of metal concentrations (CW), the authors estimated the levels that would cause the exceedance of the permissible total hazard index value ($HI_{oral} > HI_{perm}$).

A simplified prognosis for the metals analysed showed that their concentrations in treated water would have to increase at least 11 times in the case of adults and 29 times in the case of children before the risk levels related to drinking

Table 1. Expected maximum concentrations of metals that would generate an unacceptable risk HI_{oral} of treated water directed to recipients in 2012 year

Element	MAX value in fact	MAX value predict for an unacceptable risk	
		Adults	Children
	[mg/dm³]		
Cd	7.00E-04	8.40E-03	2.10E-02
Cr	2.70E-03	3.24E-02	8.10E-02
Ni	2.00E-03	2.40E-02	6.00E-02
Mn	6.70E-03	8.04E-02	2.01E-01
Pb	1.00E-03	1.20E-02	3.00E-02
Zn	5.60E-03	6.72E-02	1.68E-01
HI_{oral} unacceptable		1.072	1.029

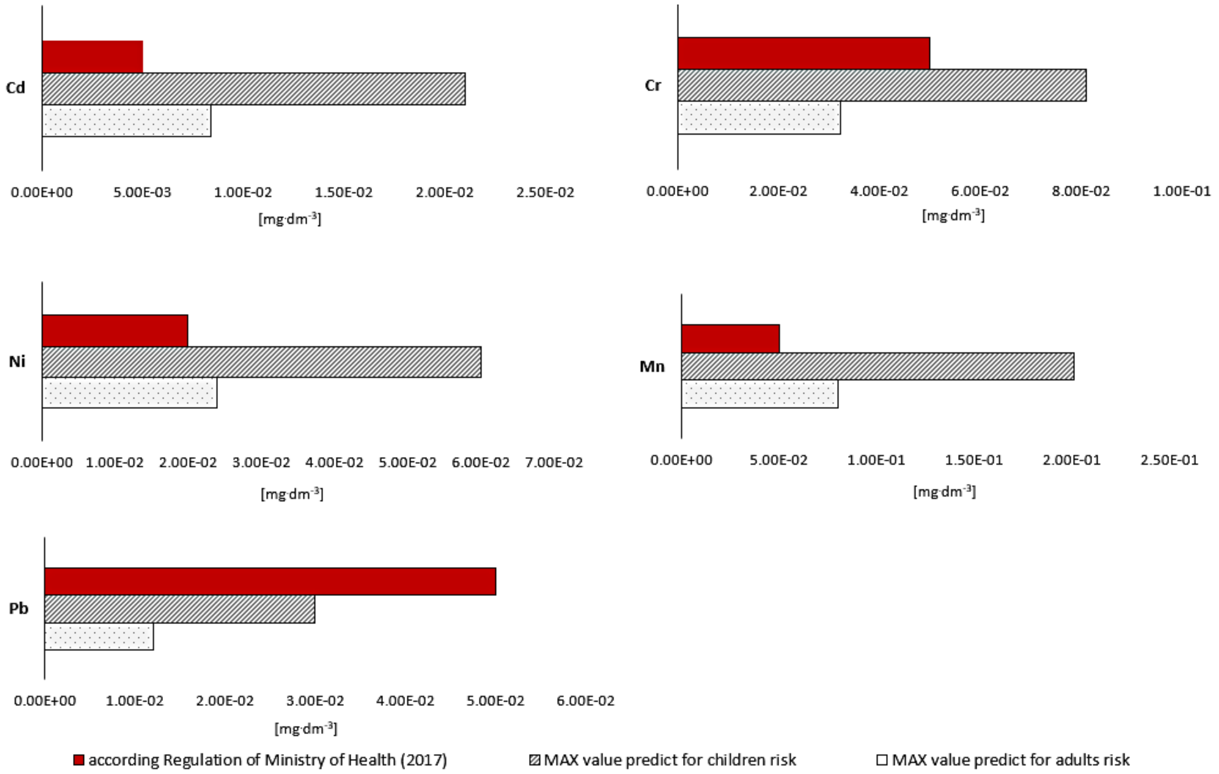


Figure 3. Comparison of the predicted concentrations of metals generating an unacceptable level of exposure via route with the limit values for drinking water according to the Regulation of the Ministery of Health [2017] for: Cd, Cr, Ni; Mn; Pb

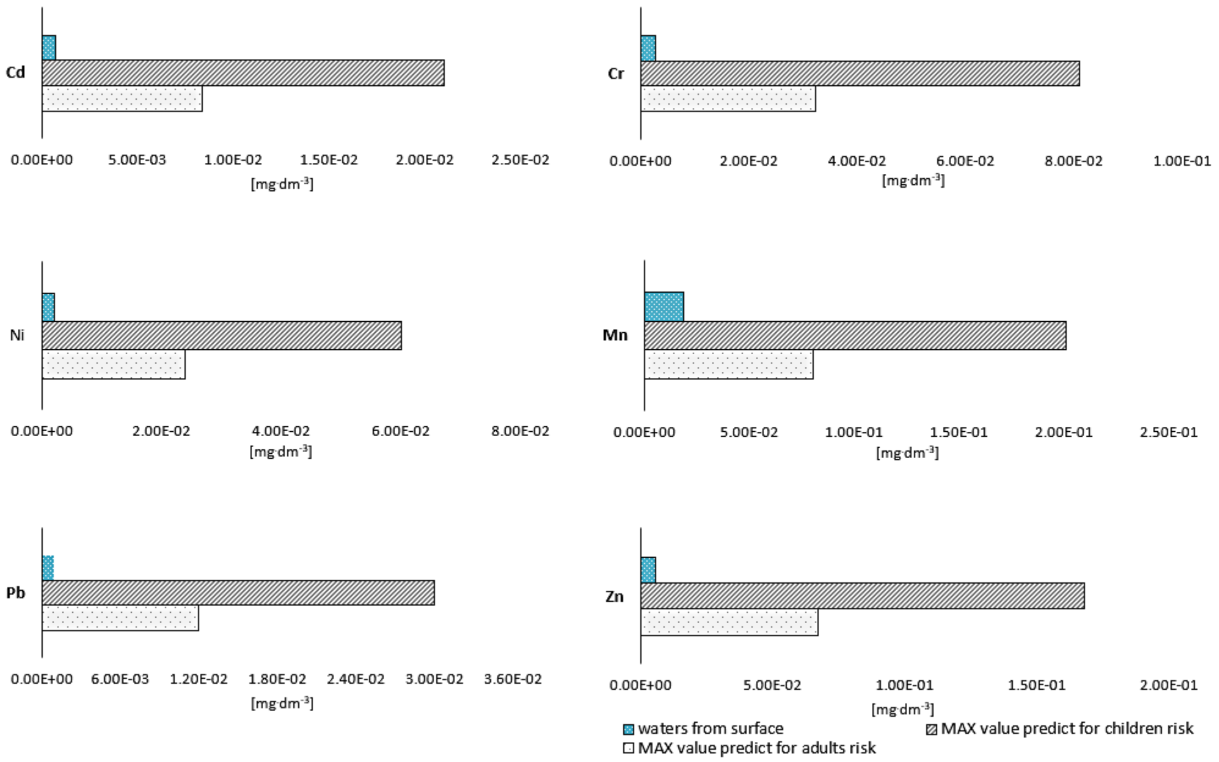


Figure 4. Comparision of the predicted concentrations of metals generating an unacceptable level of exposure by the oral route with the maximum values in the water from the Dunajec River (2012) for: Cd, Cr, Ni, Mn, Pb, Zn

water (HI_{oral}) exceed permissible values for these groups (Table 1). Only this level of metal concentration multiplication would yield the total HI_{oral} value of 1.072 in adults and 1.029 in children, exceeding the permissible value of HI = 1.

The obtained multiplied concentration values were compared with limit values for potable water (with the exception of Zn for which a limit value is not set) [Regulation, 2017]. In the case of Cd, Mn and Ni, it was found that the multiplied concentration values would exceed limit values for potable water for children and for adults (Fig. 3). This was different for Pb, as its modelled highest concentration did not exceed the permissible value (amounting to 1.00E-02 $mg \cdot dm^{-3}$) for adults and children. The modelled highest concentration of Cr would exceed the permissible level for potable water for children but not for adults.

At this point it is important to note that even the “worst” actual, maximum values obtained in the analyses of metal content in treated water used in the evaluation met the limits set for potable water provided in legal regulations [Regulation, 2017].

The highest recorded concentrations of metals in raw water supplied to WTPss were used to assess the possibility of occurrence of the predicted concentrations of metals in treated water. Due to the fact that the water treatment plants are mainly supplied with river water and water from surface intakes can be subject to quality deterioration caused by cloudburst or floods, the modelled concentrations were compared with the maximum concentrations found in raw water taken directly from the Dunajec River in 2012 (Fig. 4.). The maximum concentration of each of the metals analysed in river water was considerably lower than the modelled concentrations producing unacceptable exposure levels and amounted to only 10.84% of CW predicted for adults and 4.34% of CW predicted for children.

The metals analysed are commonly found in the environment as anthropogenic and geogenic pollutants [Kicińska & Gruszecka-Kosowska, 2016; Kosa & Kicińska, 2016; Kicińska et al., 2018; Ciuła, 2021; Ciuła et al., 2019]. An example of a metal of natural origin found in large quantities is Mn, whose greatest share in modelled CW was observed in the case of adults (23.65%). This element is commonly found in sandstone formations (Fe-Mn concretions) present in the study region, which results in its high geochemical background level. However, even though very high, the calculated quantity of this element did not pose a health hazard [Kicińska et al., 2019].

To conclude, it was found that in the current conditions, even in the case of an uncontrollable failure of the water treatment system, an unacceptable risk level would not be reached due to the incidental character of such an occurrence and the relatively short duration of the crisis situation as compared to the potential exposure time of 26 years for adults and 6 years for children assumed in the US EPA [1989] procedure. The results obtained clearly confirm the effectiveness of the technological processes employed.

Assessment of risk related to the presence of organic xenobiotics in water

The calculated non-carcinogenic (HI) and carcinogenic (CR) hazard index values for the organic xenobiotics studied were almost identical in the case of adults and children. The expected linear increase in HI and CR values for the increasing maximum substance concentrations applied was observed for both ingestion and inhalation exposure routes and for both age groups. The highest health risk was observed for the M_5 model based on a 200% increase in the concentration of the substances analysed in water. At this water quality level, the hazard index increased by 67% both in children and in adults, amounting to 5.52E-03 and 1.44E-02, respectively, while CR was 9.23E-07 for both age groups (Fig. 5, 6 and 7).

The results obtained are very satisfactory. Despite using very unfavourable calculation models, the non-carcinogenic and carcinogenic hazard indexes (for both exposure routes – ingestion and inhalation) did not reach unacceptable values in any of the scenarios. In the most unfavourable model (M_5), HI_{oral} amounted to 1.4% (in adults) and 0.55% (in children) of HI_{perm}. At the same time the HI_{inhal} values amounted to 0.3% (in adults) and 0.9% (in children) of the limit values, even when the concentration of all xenobiotics in water was increased three times.

The expected maximum carcinogenic hazard index for inhalation exposure for the so called aggregate resident was estimated at only 4.72E-09, which amounts to 0.47% of CR_{perm} ($CR_{perm}=10^{-6}$) calculated using the M_5 regression model. In the case of ingesting water with thus specified parameters, the predicted hazard indexes reached 0.17% of CR_{perm} (at +5% CW), 0.20% (at +25% CW), 0.24% (at +50% CW), 0.31% (at +100% CW) and 0.47% of CR_{perm} (at +200% CW) (Table 2).

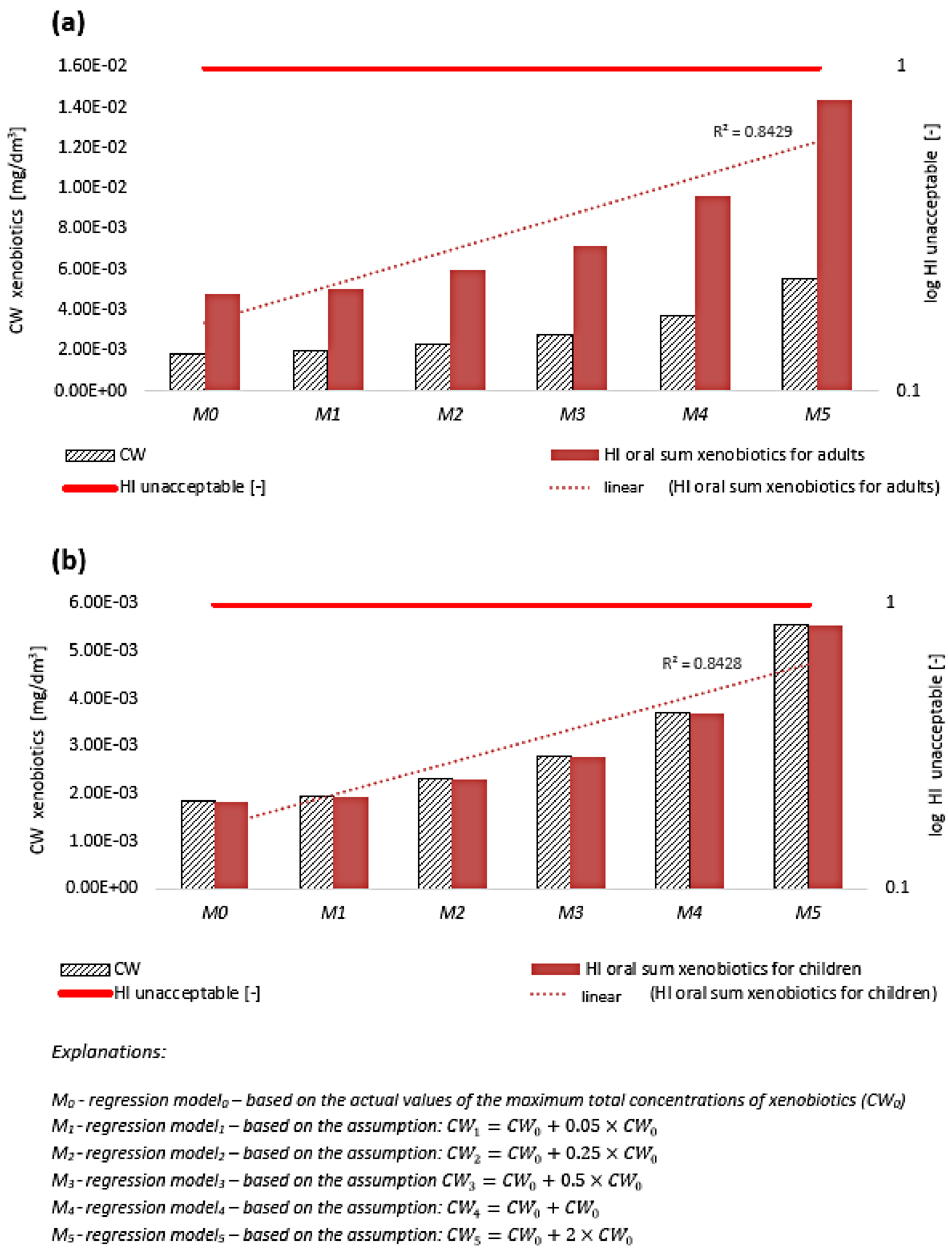


Figure 5. Regression models of non-carciogenic risk variability for the alimentary pathway of exposure ($HI_{oral\ sm}$) of selected xanobiotics for adults (a) and children (b) in treated water

In the case of non-carcinogenic hazard index calculated for the M_5 regression model, it was found that the permissible exposure value (HI_{perm}=1) was exceeded in children or adults. Assuming the worst-case scenario (M_5), the total hazard index would only amount to 10.02% and 1.54% of the permissible value for adults and children, respectively (Table 2).

The total carcinogenic hazard index for the entire life of an aggregate resident coming into contact with water whose quality is 3 times lower would not exceed the assumed permissible value (CR_{perm}). The maximum expected exposure CR_{sum} would amount to 9.28E-07, which is 92.8% of CR_{perm}. In the case of the M_0 regression model based on actual maximum concentrations of xenobiotics, CR_{sum} would be 3.08E-07, which amounts to 30.8% of CR_{perm}. It is only when the concentration of xenobiotics reached 5 times the maximum xenobiotics concentration that the permissible value CR_{perm} was exceeded by 23% (Table 2).

It is worth noting that the substance concentration values assumed for the calculation of the M_0 value were overstated, as the concentrations of xenobiotics were lower than the limit of quantitation (LOQ) of the applied method only by an

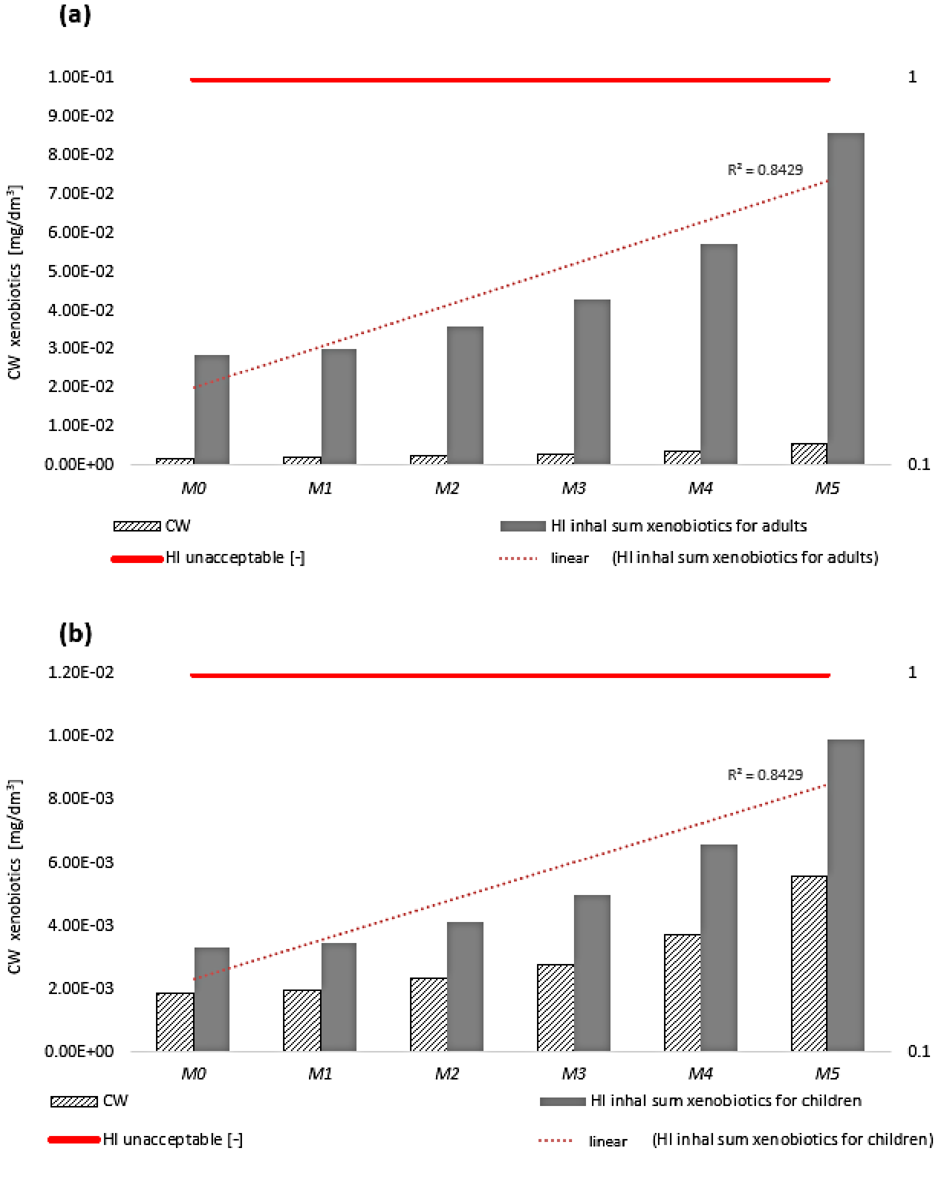
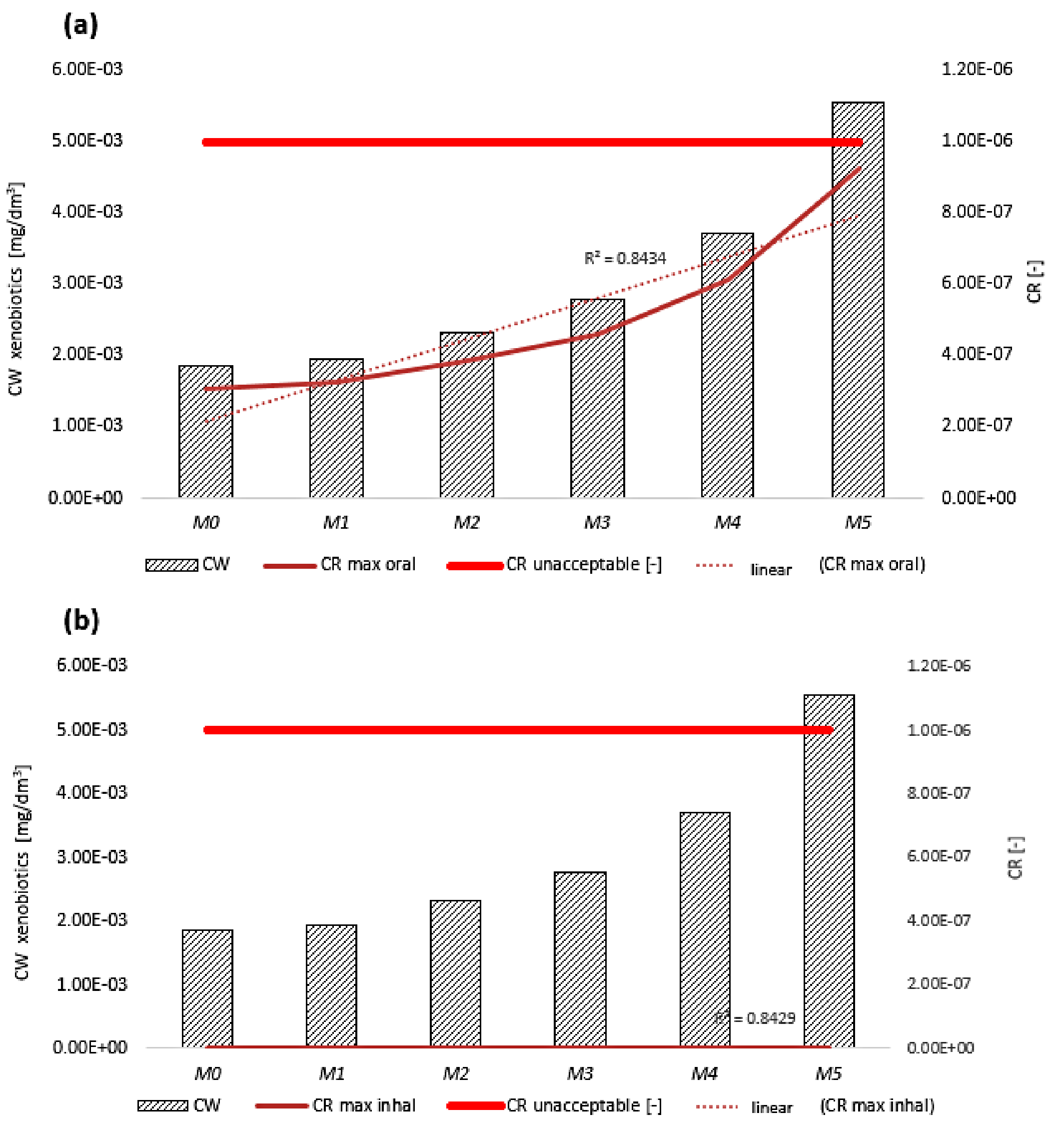


Figure 6. Regression models of non-carciogenic risk variability for the inhalation route of exposure ($HI_{inhal\ sum}$) of selected xenobiotics for adults (a) and children (b) in treated water

Table 2. Variation of HI and CR of children and adults for selected xenobiotics depending on the exposure route (1) oral, (2) inhalation for the regression models of the variability of substance concentration in water

Regression model	CW_n [mg/dm³]	CW_n increase [pkt. %]	HI_{oral} [-]		HI_{inhal} [-]		HI_{sum} participation in HI_{perm} [%]		CR_{oral} [-]	CR_{inhal} [-]	CR_{sum} participation in CR_{perm} [%]
			Adults	Children	Adults	Children	Adults	Children			
M_0	1.85E-03	-	4.79E-03	1.84E-03	2.86E-02	3.30E-03	3.34	0.51	3.07E-07	1.57E-09	30.84
M_1	1.95E-03	+5	5.03E-03	1.93E-03	3.01E-02	3.47E-03	3.51	0.54	3.23E-07	1.65E-09	32.46
M_2	2.32E-03	+25	5.99E-03	2.30E-03	3.58E-02	4.13E-03	4.18	0.64	3.84E-07	1.97E-09	38.65
M_3	2.78E-03	+50	7.19E-03	2.76E-03	4.29E-02	4.95E-03	5.01	0.77	4.61E-07	2.36E-09	46.38
M_4	3.71E-03	+100	9.58E-03	3.68E-03	4.29E-02	6.61E-03	6.68	1.03	6.15E-07	3.15E-09	61.83
M_5	5.56E-03	+200	1.44E-02	5.52E-03	8.59E-02	9.91E-03	10.02	1.54	9.23E-07	4.72E-09	92.75

Note: CW – total maximum concentration of selected xenobiotics in water; n – calculation variant of the regression model (given multiplication of the concentration value]; HI_{oral} / CR_{oral} – Sum noncarcinogenic / carcinogenic health exposure magnitude for the oral scenario; HI_{inhal} / CR_{inhal} – Sum noncarcinogenic / carcinogenic health exposure amount for the inhalation scenario.



xplanations: look at Figure 5

Figure 7. Regression models of cariogenic risk variability for the alimentary (a) and inhatation (b) exposure pathway (CR_{sum}) of selected xenobiotics in treated water

order of magnitude. The analysis of the long-term data confirms that none of the xenobiotics studied reached a concentration equal to LOQ. Therefore, it is expected that even in the case of emergencies (e.g. floods), the values assumed in the calculation models will not be reached or exceeded. Additionally, the estimated risk value reflects the potential negative impact on health in the case of chronic exposure (using the residential scenario). Therefore, the excessive concentration would have to be present in water for multiple years (in the case of carcinogens, the average exposure time is 70 years). Such concentrations were not found even incidentally in the water samples studied to date.

Assessment of risk related to the presence of microbiological pathogens in water

A model-based risk assessment has not been conducted for microbiological pollutants due to the fact that even 1 bacteria [CFU/100ml] present in potable water produces an unacceptable risk level [Regulation, 2017]. However, it is worth emphasizing the importance of microbiological safety of public water distribution systems. A study conducted in 2021 [Wysowska et al., 2021] confirmed the high effectiveness, and most importantly the stability, of the removal of microbiological pathogens from water during the treatment processes. The study results demonstrated that the water supplied from infiltration wells to WTPss and WTPs is characterised by a considerably lower level of bacteria (by about 90%) than water taken directly form the Dunajec River. The quantity of bacteria in river water reached up to 7020 CFU (in the case of *Coliform* bacteria). Based on the results of analyses conducted for both water treatment plants, it was found that at all times there was a 100% reduction in the quantity of microbiological pathogens in treated water supplied to consumers, meeting the requirements for potable water (i.e. 0 CFU). The study demonstrated that infiltration through a sand bed is a highly effective method for removing pathogenic bacteria (on average 99%) and may be an alternative to indirect water treatment processes, comparable to filtration using DynaSand filters. Furthermore, the analysis of individual technological processes phases confirmed that pre-coagulation combined with filtration using sand filters allows for reducing the presence of bacteria by between 59.5% (*Enterococcus* bacteria) and 99.8% (*Clostridium perfringens*). These processes combined with water disinfection (using UV light and chlorine gas) have a positive impact on epidemiological safety.

Based on a thorough analysis of the results obtained in the years 2012–2019, it was decided not to proceed with the evaluation of health risk related to bacteriological pollution. The multiplication of the number of bacteria could be correlated with the health risk posed to consumers of water from the public distribution system. The water treatment technologies in place allow for removing 100% of pathogens from water. The subject literature confirms that disinfection using ozone (used in both water treatment plants studied) and adsorption using activated carbon (used in WTPss) are the most effective ways of inactivating bacteria, while the least effective method is the use of chloramines [Kowal & Świderska-Bróż, 2005].

It is worth noting that there still exists a problem of epidemiological health risk related to the consumption of low-quality water from private water intakes. Research conducted in the years 2015–2018 [Wysowska et al., 2020] demonstrated considerable health risk caused by *Enterococcus faecalis*, *Coliform* bacteria and *Escherichia coli*.

CONCLUSIONS

The analyses conducted within the present study demonstrated that the proposed approach to model-based risk assessment using simple regression models may become a tool supporting the management of health risk and the operational safety of public water distribution systems. The increase in health risk related to the decrease in water quality is linear for both inhalation and ingestion exposure. This reflects the assumption that the concentration of a given parameter in the medium studied (water) affects the exposure level. In the least favourable exposure scenario, assuming the presence of organic xenobiotics in potable water, the total non-carcinogenic hazard index amounts to only 10% of the permissible value in adults and 1.5% in children. In the case of xenobiotics, even if the quality of water decreased 3 times, the total carcinogenic hazard index calculated for life-long exposure of a resident to polluted water did not exceed the permissible value (CR_{perm}). Concentrations of metals in treated water would have to increase 11 times in the case of adults and 29 times in the case of children, as compared to the least favourable values recorded (in 2012), before ingestion exposure generated an unacceptable risk, which does not occur in present conditions.

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